National Snow and Ice Data Center
Cooperative Institute for Research in Environmental Sciences

Validation Studies and Sensitivity Analyses for Retrievals of Snow Albedo from EOS AM-1 Instruments

Progress Report for 1999-2000 Work

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May 20, 2000

1. Background

1.1 Project Summary

As part of NASA's effort to map and characterize the Earth system from space, this investigation is engaged in validating snow albedo retrievals from instruments on board Terra, the Earth Observing System satellite. Surface albedo, the surface hemispheric reflectivity integrated over the solar spectrum, is a fundamental component needed for determining the radiation balance of the Earth-atmosphere system. Because snow is strongly forward scattering and has a variable albedo across the solar spectrum, spaceborne measurements in a few channels and one or few viewing angles are not representative of the spectrally-integrated albedo. In addition to validation activities, we are also undertaking sensitivity studies to investigate how atmospheric properties, topographic complexity and spatial resolution affect albedo retrievals.

Surface albedo will be one of the standard data products to be generated from data acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument. The Multiangle Imaging SpectroRadiometer (MISR) requires characterization of the angular reflectance characteristics over snow. A critical concern is the current lack of an aerosol retrieval method that provides accurate estimates over snow-covered surfaces. This prevents accurate atmospheric correction of MODIS and MISR data over snow. Through a combination of model simulations and field validation experiments (both pre-launch and post-launch) this research is validating a scheme for converting measurements of snow bidirectional reflectance to snow albedo for both MODIS and MISR. A narrowband-to-broadband conversion is being developed and tested for both instruments allowing intercomparison of broadband albedo retrievals between MODIS and MISR. In sensitivity analyses, we are evaluating how atmospheric characterizations and digital elevation model errors affect the accuracy of the albedo retrievals.

1.2 List of Objectives

1. Evaluate snow albedo retrievals from MODIS and MISR
   - Validate snow BRDF model
   - Quantify sensitivity of snow albedo estimates to atmospheric variables
   - Quantify effects of DEM inaccuracies on snow albedo estimates
2. Develop and test a narrowband-to-broadband snow albedo conversion scheme for MODIS and MISR
3. Perform intercomparisons of broadband snow albedo estimates from MODIS and MISR

2. Scientific Accomplishments

2.1 Snow BRDF Modeling Results

The DIScrete Ordinates Radiative Transfer (DISORT) model (Stamnes et al., 1988) has been used to model the directional-hemispherical and angular spectral reflectances from snow for user defined snow properties (grain size, density, layering, depth), illumination and viewing geometries, and atmospheric conditions. Mie theory is used to calculate single particle scattering and absorption. The model is used to convert remotely sensed measurements of bidirectional reflectance to surface albedo. Conversion factors are determined from the model runs and stored in a lookup table. Part of this investigation is to provide further validation for this conversion approach. We have completed numerous runs of the model have been tested to examine the effects of different snow properties on the BRDF of snow. These include snow grain size, concentrations of light absorbing impurities, snow depth and the proportion of diffuse and direct irradiance.

Validation of the model was done through comparison to calibrated ground-based measurements from PARABOLA and the ASD FieldSpec FR spectrometer. PARABOLA measures the spectral hemispherical-directional reflectance factor (HDRF) over the upward and downward hemispheres, in angular increments of 5^{o}. It has eight channels (0.44, 0.55, 0.65, 0.86, 0.94, 1.03, 1.665, and a PAR band). A calibrated Spectralon target is viewed at the end of each sequence of angular measurements (approximately every 3 minutes) for use in determining reflectance. Since our progress report last year, we re-calibrated the results of the PARABOLA measurements from March 1998 and fixed a problem in our plotting routine. Modeled HDRF values match the scattering pattern that we see in the PARABOLA data, both in terms of forward scattering peak and nadir reflectances. Spectral albedos were calculated by integrating HDRF values over the downward-looking hemisphere. Instrument self-shadowing was problematic and was removed from the albedo computation by interpolating values over the narrow shadow region. The range in HDRF values and the narrowband albedo estimates both agree closely with their counterparts as calculated by the DISORT model. Areas of disagreement appear to result from surface roughness (on the 1-cm to 10-cm scale). We are looking into this further in our fieldwork in Greenland (see Section 4.1).

We also performed some preliminary topographic sensitivity tests using the model. We found the highest sensitivity for shortwave infrared HDRF values, with as much as 20% difference between values in the forward scattering peak for a 10^{o} difference in the angle of solar incidence. We will continue these sensitivity tests and are working on developing a means for constraining the albedo solution using multiangle observations available with MISR. This also points to the need for accurate digital elevation model (DEM) data. We have acquired what are currently considered to be the most accurate DEM data for the Greenland ice sheet and will use these in our post-launch validation efforts in Arctic. For our work over North America, we will continue to use the USGS 30-m DEM data.

2.2 Narrowband-to-Broadband Albedo Conversion

2.2.1 Model Development

For the conversion from narrowband satellite measurements to a broadband albedo, we assume that we can parameterize the albedo equation as in Equation 1:

$$\alpha = \frac{\rho_i S_i \Delta\lambda_i}{S_i \Delta\lambda_i} \tag{1}$$

where, α is broadband albedo, ρ is reflectance in channel i, S is the downwelling solar irradiance over the spectral range $\Delta\lambda$. We subdivide the numerator into different channels, depending on the number of channels available for each sensor. We assume that Eq. 1 can be parameterized by a corresponding narrowband reflectance accompanied by appropriate conversion factors f_I where i=1,n number of channels. Thus, for MODIS band 1 (620-670 nm) and band 2 (841-876 nm), the broadband albedo can be parameterized as in Equation 2:

$$\alpha = \frac{1/f_1\ \rho_1 S_1 \Delta\lambda_1 + 1/f_2\ \rho_2 S_2 \Delta\lambda_2}{S_i \Delta\lambda_i} \tag{2}$$

Eq. 2 therefore shows that the broadband albedo is a linear combination of the narrowband albedos. Thus, the problem becomes one of estimating the appropriate conversion factors. It is important to examine how these conversion factors may vary with changes in atmospheric and snow surface conditions. Using the 6S model, we computed changes in conversion factors for varying water vapor, aerosol optical depth and solar zenith angle. For small-to-moderate changes in atmospheric column water vapor and aerosol optical depth, the factors change very little. However, for large aerosol optical depths (0.5), there will be changes in the conversion factors for the visible part of the spectrum. Solar zenith angle affect conversion factors in all wavelength bands.

We have developed a set of preliminary conversion factors for MODIS bands 1 and 2 and bands 3-7 using a multiple linear regression approach. In this approach, the objective is to build a probabilistic model that relates the broadband albedo to a linear combination of predictor variables. The general form of the model is shown in Equation 3:

$$\alpha = \beta 0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \qquad (3)$$

The full model parameters include the following:

- Narrowband albedos (bands 1&2, 3-7)
- Solar zenith angle (0-85^o, in increments of 5^o)
- Aerosol optical depth (0.01, 0.05, 0.10, 0.50)
- Atmospheric model (Arctic Winter, Arctic Summer)
- Aerosol model (continental, maritime, urban, dust-like)

For MODIS bands 1 and 2, the full model consists of 6 variables and for MODIS bands 3-7, there are 9 variables in the full model. Tables 1 and 2 show the full model results for the two different MODIS cases.

Table 1. Regression results for MODIS bands 1 and 2. Correlation coefficient r=0.961, unexplained variance for the full model SSE=0.03167.

Variable	Coefficient	Standard Deviation	T-value	P-value
β_0	-2.311291			
β_1 (Channel 1)	3.307848	0.63796	5.18503	0.0000
β_2 (Channel 2)	-0.107222	0.17546	-0.61109	0.5414
β_3 (Solar zenith angle)	-0.000230	4.998E-05	-4.59813	0.0000
β_4 (Aerosol optical depth)	-0.030526	0.00164	-18.6671	0.0000
β_5 (Atmospheric model)	-0.017374	0.00062	27.9452	0.0000
β_6 (Aerosol model)	-0.000166	0.00028	-0.59615	0.5513

Table 2. Regression results for MODIS bands 3--7. Correlation coefficient r=0.965, unexplained variance for the full model SSE=0.02827.

Variable	Coefficient	Standard Deviation	T-value	P-value
β_0	-9.11051			
β_1 (Channel 3)	3.56455	1.02353	3.48260	0.0005
β_2 (Channel 4)	6.66208	0.89926	7.40838	0.0000
β_3 (Channel 5)	-0.45808	0.06701	-6.83591	0.0000
β_4 (Channel 6)	2.33251	0.38814	6.00948	0.0000
β_5 (Channel 7)	-2.75162	0.52407	-5.25039	0.0000
β_6 (Solar zenith angle)	-0.00012	5.62E-05	-2.21913	0.0269
β_7 (Aerosol optical depth)	-0.03537	0.00165	-21.39949	0.0000
β_8 (Atmospheric model)	0.01757	0.00059	29.81206	0.0000
β_9 (Aerosol model)	-0.00010	0.00026	-0.38798	0.6982

To test whether we can remove some variables from the full model, we compute the test statistic f:

$$f = \frac{(SSE_1 - SSE_k)/(k-1)}{SSE_k / [n-1(k+1)]} \qquad (4)$$

where, SSE_k is the corresponding sum of the squared errors for the full model and SSE_l is the sum for the reduced model. For example, if we remove the aerosol model variable from the full model, we find that f=0.3593 for Table 2 and f=0 for Table 3. Both of these are less than the critical value for significance at the 0.01 level so we conclude that a reduced model can neglect the aerosol models as predictor variables. After further tests, results indicated that, for MODIS bands 1&2, the appropriate model should include solar zenith angle and aerosol optical depth, but not the other predictor variables. The appropriate regression model for MODIS bands 3-7 requires aerosol optical depth but not solar zenith angle nor the other predictor variables. However, if we split aerosol the variables into low aerosol optical depth (≤0.10) and high aerosol optical depth (0.50) and re-run the regressions, it appears that a different model is required for the high aerosol optical depth. Results for the low aerosol optical depths changed the number of parameters needed for the MODIS bands 3-7 model. It showed that including solar zenith angle significantly improved model estimates of broadband albedo. Preliminary results in which water vapor amounts are included as a predictor variable indicate that water vapor is does not significantly affect broadband estimates.

In upcoming work, we will develop conversion coefficients for the four MISR channels using this regression-based approach. We will then assess the MISR and MODIS narrowband-to-broadband conversion models using ground-based data and tune the conversion coefficients as needed.

2.2.2 Validation of Narrowband-to-Broadband Conversion

Our approach to validating the narrowband-to-broadband conversion coefficients for MODIS and MISR is to compare ground-based narrowband and broadband albedo values with satellite-derived narrowband and broadband albedos. This requires a homogeneous snow-covered surface to eliminate mixed-pixel effects. A flat surface is also preferred to reduce topographic effects on the validation. In addition, it is important to characterize the atmospheric conditions.

For each daytime Terra overpass, we acquire ground-based spectral albedo data using an ASD FieldSpec FR instrument with a remote cosine collector. Broadband snow albedo data are collected using an Eppley PSP. Atmospheric measurements are made using a Reagan sun photometer. We characterize the snow physical properties (density, grain size, stratigraphy) from snow pits.

We are also testing and evaluating the effects of surface roughness on the multiangle observations from MISR. To quantitatively characterize small-scale surface roughness, we have developed a simple measuring device that can be easily transported in the field. This “roughness meter” consists of a length of laminated paper (3 m × 1m) that is gridded at 1-cm resolution. It is held taught by vertical poles at either end and inserted into a shallow trench in the snow where it is photographed with a digital camera. Undulations on the snow surface are superimposed on the grid and can thus be quantified.

2.3 Field Experiments, Winter-Spring 2000

Our primary post-launch field experiment was intended to be February 10-20, 2000 in Wisconsin. This campaign was termed the Wisconsin Ice/Snow Campaign-Terra2000 (WISC-T2000) and involved other MODIS investigators from NASA/Goddard and the University of Wisconsin. However, multiple factors (launch delays, delays in opening the Earth-viewing doors, conflicts in the ER-2 schedule) forced a delay in the start of our field campaign until February 26. By that date, the snow on the ground in Wisconsin had melted, causing us to cancel our participation in the WISC-T2000 campaign.

Following the WISC-T2000 attempt, we attempted to gather ground-based broadband and spectral snow albedo and atmospheric characterization measurements at sites in the Colorado Rockies. Again, we were thwarted by cloud cover on Terra overpass dates in March and early April followed by early snow melt.

We were able to make some limited measurements on April 5th at Turquoise Lake, Colorado. Figure 1 shows a MISR red band image at 275m spatial resolution. We collected broadband snow albedo (Eppley PSP) and spectral snow albedo (ASD-FR with cosine collector) as well as atmospheric optical depth measurements using a sun photometer (ASD-FR with telescope). Figure 2 shows the broadband albedo measurements. The ASD albedo and photometer data are still in the process of being calibrated. We recently ordered and received MODIS and MISR calibrated radiance data for Turquoise Lake and will convert the TOA radiances surface albedo as soon as the sunphotometer measurements are calibrated and can be converted to optical depths. We expect to have this completed by July 2000.

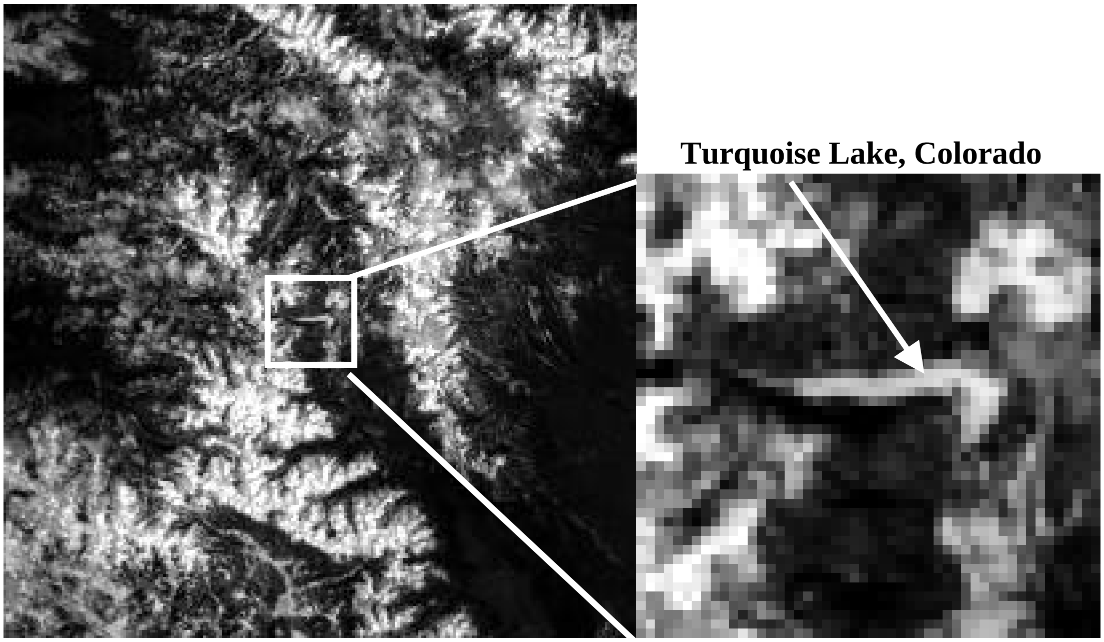

Figure 1. MISR image of Turquoise Lake with close-up on the right. The lake is approximately 12 km long by 2 km wide at it's widest point. At the time of the Terra overpass, the lake was snow-covered with snow depths averaging about 12 cm and snow grain radius about 500 μm.

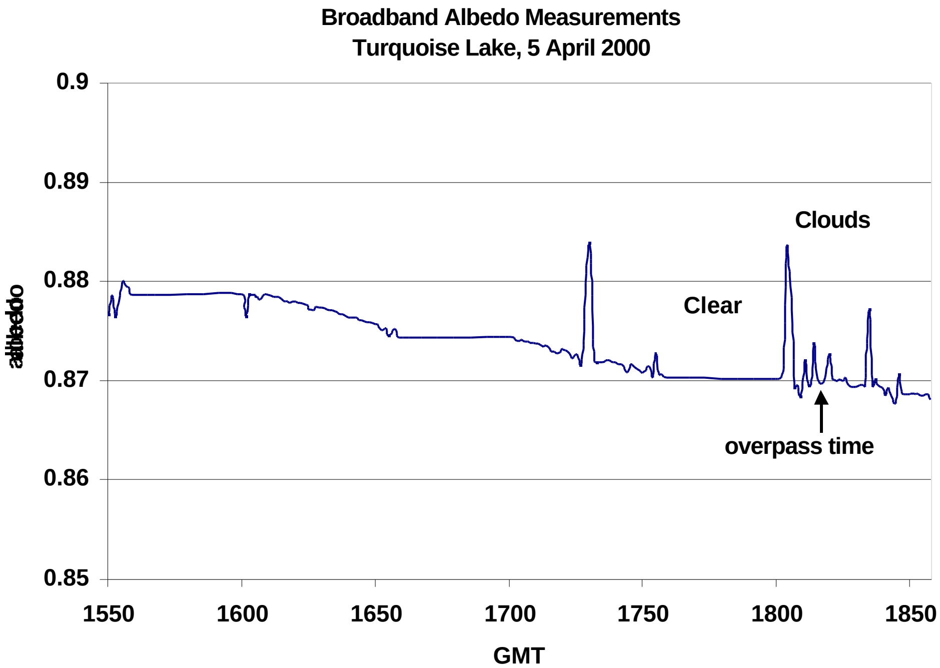

Figure 2. Broadband albedo (Eppley PSP) measurements at Turquoise Lake for April 5, 2000. Clear sky broadband albedo was 0.87 just 1 hour prior to the overpass. Scattered clouds were present at the time of the overpass.

Although we had a number of serious difficulties with fieldwork this year, we have been able to take advantage of an opportunity to participate in a field campaign on the Greenland ice sheet (with Dr. Koni Steffen, University of Colorado). Currently, Dr. Stroeve is at the ETH/CU camp on the western part of the ice sheet making a full-range of measurements needed to test the coefficients for the narrowband-to-broadband conversion. She will return to the US on June 8, 2000. The location and time of year are highly advantageous for our investigation because there are numerous Terra overpasses over the high latitudes and nearly continual sunlight. We also expect to have changing snow conditions because the ice sheet surface warms and begins to melt at this time of year – thus, this should provide a wider range of snow albedo values.

3. Programmatic Efforts

3.1 Collaborations

We continue to work closely with members of both the MISR and MODIS Science Teams. On the MODIS side, we are working with Dr. Dorothy Hall's group to coordinate validation objectives, priorities and activities. We co-authored an article about our validation efforts that was published in The Earth Observer and we have submitted a co-authored manuscript to Hydrological Processes in which we describe the development of the prototype MODIS snow albedo algorithm.

Collaborations with the MISR team have also been very successful. The MISR validation group supported our efforts in Wisconsin this February, providing instrumentation and technical support for our ground experiment. In March, Dr. Nolin was selected as a new member of the MISR Science Team. Along with other members of the MISR team, Drs. Nolin and Stroeve were both co-authors in a publication highlighting the utility of multiangle observations in Earth science.

In related work, we are involved in an EO-1 investigation entitled “Advancing Glaciological Applications of Remote Sensing with EO-1” (Robert Bindschadler, PI). We will be calculating broadband albedo from Hyperion instrument on the EO-1 satellite using direct integration over the numerous spectral channels and comparing these estimates to our regression-based broadband estimates from MODIS and MISR. We share many validation sites between the two projects and anticipate that the comparisons will yield useful information about the different sensors and approaches to computing albedo, particularly with regard to spectral vs. multiangle approaches.

We are also working with Dr. Jiancheng Shi, of the University of California, Santa Barbara who is performing validation of the snow covered area retrievals over alpine regions for the MODIS instrument. We intend to share data and results with Dr. Shi and, through our mutual collaborations with Dr. Hall, we will maximize our validation efforts and eliminate any possible redundancies.

3.2 Data archive and distribution

Currently, the primary archive site for our validation data is on the P.I.'s and Co-I's computers. Data distribution is via the project home page or via contact with the P.I. We will be transitioning the data to a permanent archive and distribution site at the National Snow and Ice Data Center (NSIDC) in the final year of the project. NSIDC will advertise the data via it's web-based Data Catalog and data will be distributed via ftp. For an example of web-based access through the NSIDC Data Catalog, see the following website: http://www-nsidc.colorado.edu.

4. Tasks for 2000-2001

4. 1 Narrowband-to-Broadband Albedo Conversion

Our first priority for the final year of this investigation is to acquire and analyze in situ and satellite-derived albedo data, and atmospheric characterization measurements from field experiments in Greenland, Colorado, and Montana. We will use these data to test and refine model-derived conversion coefficients for MODIS channels 1-2 and 3-7 and will use our regression approach to develop conversion coefficients for MISR channels 1-4. Satellite-derived broadband albedo measurements will then be compared with ground-based broadband albedo data collected at the validation sites listed below:

- Greenland Climate Network (GC-Net, 15 automated weather stations on the ice sheet)
- Niwot Ridge, CO (LTER site)
- Mammoth Mountain, CA (UCSB site)
- Fort Peck, MT (SURFRAD site)

These sites represent snow conditions for a variety of locations including polar, alpine-continental, alpine-maritime, and Northern Great Plains. Each site is equipped with upward and downward-looking pyranometers and additional measurements of atmospheric characteristics are also available at Niwot Ridge, CO and Fort Peck, MT.

Our second priority is to continue validation of the HDRF-to-albedo conversion approach (using the DISORT model and look-up table). As originally intended for WISC-T2000, we will participate in another field experiment (described below) in which we will acquire PARABOLA data for comparison with model output.

Topographic sensitivities will be further investigated using a modeling approach in which we degrade the accuracy of the DEM over a site (essentially "tilting" the surface) and compare satellite-derived albedo values with surface measurements. Using the DISORT model, we will test the sensitivity of albedo estimates to changes in illumination geometry for each of the MODIS and MISR channels as well as for broadband albedo estimates. This is especially important for determining the error budget of albedo estimates over alpine regions.

Field Experiments for Winter 2000-2001

Because of problems with our WISC-T2000 campaign last year, we intend to use our flight hours for a field campaign at the SURFRAD site near Fort Peck, MT during February 2000. The MISR validation team may also participate (as in past years) but as yet this is not confirmed. We have four flight hours for the ER-2 remaining from last year and plan to have MAS and AirMISR on board the aircraft. Ground-based measurements will include atmospheric characterization, measurement of snow properties, snow spectral reflectance and snow albedo.

Collaborations

We will continue and strengthen our collaborations with MODIS and MISR Science team members. Dr. Nolin is a newly selected member of the MISR Science Team and remains a MISR Team Associate. As in past years, we anticipate that the MISR validation group will assist us in making ground-based measurements in our fieldwork next winter. In addition, we are working closely with Dr. Dorothy Hall and Dr. Andrew Klein (Texas A&M) in developing and testing the MODIS albedo algorithm. We have submitted a publication to Hydrological Processes and anticipate additional joint publications in the coming year. We plan to attend all MODIS and MISR team meetings in the coming year.

Timeline:

Oct – Dec 2000	Complete analysis of narrowband-to-broadband albedo data from Greenland campaign, write up results, present at AGU and submit for publication
Jan 2001	Complete model-based topographic sensitivity analyses
Feb 2001	Field experiment in Fort Peck, MT with NASA ER-2, ground-based measurements with MISR validation group
Mar – May 2001	Analyze field experiment data, complete validation of HDRF-to-albedo approach, narrowband-to-broadband conversion coefficients
Oct 2000 – Jul 2001	Analyze validation site data, compare with satellite (ongoing)
Aug – Sept 2001	Prepare data sets in final form, write up results and submit for publication

List of Publications for 1999-2000

Klein, A. G., D. K. Hall, and A. W. Nolin, Development of a prototype snow albedo algorithm for the NASA MODIS instrument. *Submitted to Hydrological Processes*.

Nolin, A. W. and S. Liang, Progress in bidirectional reflectance modeling and applications for surface particulate media: Snow and soils, Remote Sensing Reviews, *in press*.

Nolin, A. W. and A. Frei, Remote Sensing of Snow and Snow Albedo Characterization for Climate Simulations, chapter in: “Remote Sensing and Climate Simulations: Synergies and Limitations”, Edited by Martin Beniston, *Advances in Global Change Research*, Kluwer, The Netherlands, *in press*.

Nolin, A. W. and Stroeve, J. C. , Snow albedo determination and validation for MODIS and MISR. Proc. of the 2nd International Workshop on Multiangular Measurements and Models. Ispra, Italy, p. 41, 1999.

Diner, D. J., G. P. Asner, R. Davies, J-P. Muller, A. W. Nolin, B. Pinty, C. B. Schaaf, and J. Stroeve, New directions in Earth observing: Scientific applications of multi-angle remote sensing, Bull. Am. Meteorol. Soc., 80, 2209-2228, 1999.